# Silicon Schottky Barrier Diode with Near-Ideal I-V Characteristics

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*Metal-semiconductor diodes with near-ideal forward and reverse I-V characteristics have been fabricated using PtSi contacts and diffused guard rings. Typically, for a device with an area of $2.5 \times 10^{-6}$ $cm^2$ made on an n-type ⟨111⟩ oriented, 0.35 ohm-cm silicon epitaxial substrate, the forward current follows the expression $I_f = I_s \exp(qV/nkT)$ over eight orders of magnitude in current with $I_s = 10^{-12}$ A and $n = 1.02$. The reverse breakdown is sharp and occurs at the theoretical breakdown voltage of $p^+n$ silicon junctions of the same n-type doping. The premature breakdown observed in nearly all previous Schottky barrier diodes has been shown to be caused by electrode sharp-edge effects. Besides giving sharp breakdown voltage, the guard ring also eliminates anomalously high leakage currents, yet still retains the fast recovery time characteristic common to other Schottky barriers. Typically, the recovery time measured at 10 ma is less than 0.1 ns, the resolution of the measurement.*

## I. INTRODUCTION

Metal-semiconductor (or Schottky) barriers have been studied extensively in the past few years. The main concerns are the barrier height and the current transport in the metal-semiconductor system; the former has been reviewed recently by Mead,[1] and the latter discussed by Crowell and Sze.[2] Most emphasis has been placed on the forward current-voltage characteristic, which relates intimately to the electronic applications of Schottky diodes such as varistors for logic gates and microwave downconverters. The reverse current-voltage characteristic of a conventional planar Schottky diode,[3] usually has had greater leakage current and lower breakdown voltage than a diffused p-n junction. Because of this "soft" reverse characteristic, Schottky diodes have not been considered for power application, as well as IMPATT oscillators.

It should be pointed out, however, that if the reverse characteristic can he improved substantially, a Schottky diode with its inherent majority transport property, can he used as a high-speed switch in which there is virtually no minority carrier storage, and as a high-power rectifier or high-frequency oscillator where the region of greatest heat dissipation is located right at the metal-semiconductor interface and therefore the heat can be more readily conducted away.

The soft breakdown of conventional Schottky diode is not caused by the electron tunneling effect but results mainly because of the "edge effect" shown in Fig. 1(a), wbere bigh-field concentration gives rise to excess leakage current and low hreakdown voltage. The tunneling effect is ruled out because of the fact that even at very large electric fields ($\sim 5 \times 10^5$ V/cm), there is negligihle contribution of the tunneling current component to the total conduction curent,[2] owing to the relatively large electron effective mass in silicon such that the tunneling prohability of electrons from the metal to the semiconductor conduction hand is very small.

This paper presents one method to eliminate this edge effect: the diffused guard-ring method. This method has been used on planar p-n junction devices[4] to eliminate the junction curvature effect. It is shown in this paper that the guard ring improves both the forward and reverse characteristics of the Schottky diode. It is also demonstrated for the first time that the measured breakdown voltage of a Schottky junction is equal to the theoretical value of a one-sided abrupt p-n junction with the same hackground doping concentration. In addition, the surface field effect associated with the metal-inulator- semiconductor structure on the junction hreakdown is studied.

## II. EXPERIMENTAL PROCEDURE AND RESULTS

### 2.1 *Device Fabrication*

In order to study the effect of a junction guard ring on the *I–V* characteristics of a metal-semiconductor barrier, three kinds of structures were fabricated on a single wafer as shown in Fig. 1. Fig. 1(a) is a planar PtSi–Si Schottky diode alone; Fig. 1(h) is the diffused p-n guard ring alone; and Fig. 1(c) contains both a PtSi–Si Schottky barrier and a p-n junction wbich serves as its guard ring.

Most of the wafers used in the study were *n*-type silicon materials, with 2 to 8 $\mu$m thick epitaxial layers, ⟨111⟩ oriented, 0.3 to 1.2 ohm-cm. The hasic steps of fahricating the Schottky diode with a guard ring were: the wafers were first cleaned and degreased; silicon dioxide

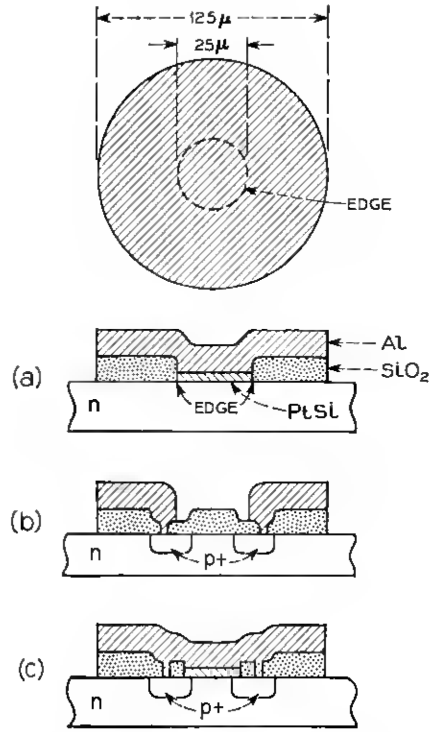


Fig. 1 — (a) Planar PtSi Schottky diode. (b) Diffused p⁺n junction ring. (c) PtSi Schottky barrier with a p⁺n guard ring as in b.

layers of about 5000 Å were then grown thermally. Diffusion rings were then cut in the oxide by the standard photoresist technique. After the junctions were boron-diffused, another $SiO_2$ layer was grown on the surface, and photoresist was used to define the center hole for platinum deposition.

In order to produce a metal-semiconductor interface comparable in uniformity to a diffused p-n junction it is required to start with a "clean" silicon surface. Even the most efficient chemical methods leave several atomic layers of inorgonic films. In this study, the silicon surfaces were back-sputtered with argon ions (at a pressure of 20 microns) using the setup shown in Fig. 2. Cathode 1 was excited with an RF oscillator, producing a plasma over the sample, and removing any films previously formed. Then a DC voltage was applied to cathode 2, and a 500 Å platinum film deposited. Heating the sample in the

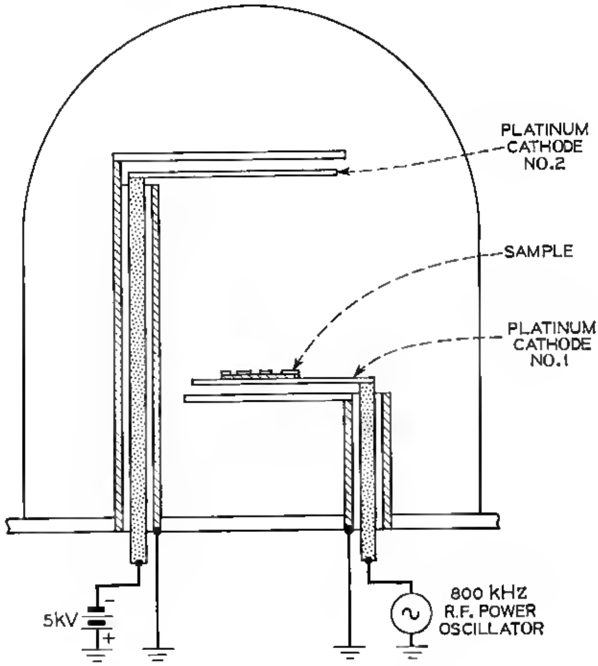


Fig. 2 — Platinum sputtering system.

vacuum chamber to 600°C caused the platinum film to react with the exposed silicon surface. For a clean surface, the reaction proceeded to the most stable phase of the system Pt–Si, forming the compound PtSi. This reaction, verified by X-ray analysis, is strongly influenced by the actual cleanliness of the interface.

The platinum layer deposited on the $SiO_2$, which did not react with the exposed silicon, was then removed by aqua regia. The final overlay metal contact was made by evaporation of aluminum and another photoresist to isolate each device. The back contact was formed by evaporation of gold and alloyed at 400°C. The three different structure shown in Fig. 1 were made at the same time on the same wafer by using multiple patterns on the photoresist masks.

### 2.2 *Forward I–V Characteristics*

Figure 3 shows the measured forward $I$–$V$ characteristics for the three structures as shown in Fig. 1. The epitaxial thickness is 2 $\mu$m, and the background doping is $2.2 \times 10^{16}$ cm$^{-3}$. The diffused junction

depth is about 1 $\mu$m. The guard ring has an area of $2.9 \times 10^{-5}$ cm$^2$ and the Schottky junction of $2.5 \times 10^{-6}$ cm$^2$. One notes that the current of the Schottky diode with a guard ring (from now on, we call it diode $c$ referring to Fig. 1c) follows the expression $I_f = I_s \exp (qV/nkT)$ over eight orders of magnitude with $I_s \cong 10^{-12}$ amp and $n = 1.02$. From the saturation current and tbe area of the diode ($2.5 \times 10^{-6}$ cm$^2$) a barrier height of 0.85 eV for the PtSi–Si barrier is obtained, in agreement with the previously reported results.[3]

For the planar Schottky diode without a guard ring (diode $a$) it is apparent that the $I$–$V$ characteristic is much inferior and gives about two to four orders of magnitude excess current at lower bias. The forward $I$–$V$ characteristic of the p-n junction guard ring is shown in Fig. 1(c). It is clear that the guard ring helps to eliminate the edge leakage current which has normally existed in a planar Schottky diode. By the use of lower resistivity and a thinner epitaxial layer, it is ex-

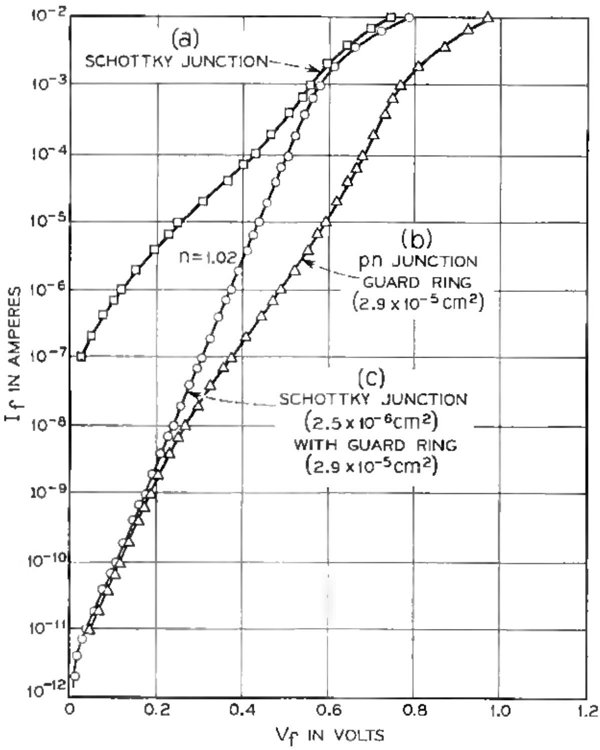


Fig. 3 — Forward current-voltage characteristics of devices shown in Fig. 1.

pected that one can obtain an exponential current range (with constant $n$-value) even larger than the present eight orders of magnitude.

### 2.3 *Reverse I–V Characteristics*

The Schottky diode with a guard ring also has a superior reverse *I–V* characteristics. For diode *a* the breakdown voltage is only 5 V (at 1 ma). The breakdown voltage for diode *b* is 27 V. About the same breakdown voltage is obtained for diode *c* which is shown in Fig. 4 for two different areas of the Schottky diodes. For small area, the space-charge generation and recombination current of the p-n junction guard ring dominates the reverse leakage current. For larger area, however, the reverse current approaches the ideal Schottky

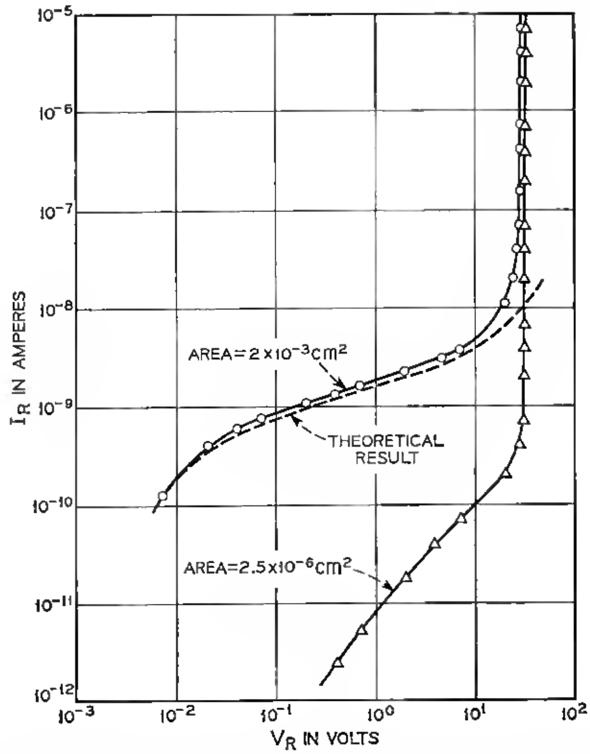


Fig. 4 — Reverse current-voltage characteristics of Schottky diodes (type c in Fig. 1). For the small diode, the area of the Schottky diode is $2.5 \times 10^{-6}$ cm² and and that of the guard ring is $2.9 \times 10^{-6}$ cm². For the larger one, the areas are $2 \times 10^{-3}$ cm² and $1.5 \times 10^{-4}$ cm², respectively.

barrier current due to image-force lowering (the dotted line is calculated using an image-force dielectric constant of 12).[5] The breakdown voltages in diodes $b$ and $c$ are in good agreement with the theoretical calculation shown in Fig. 5. This figure shows the breakdown voltages for Si $p^+n$ junctions as a function of the background doping with the junction depth as a parameter.[6]

For planar diffusion through a photoresist mask, the impurities will diffuse both downward into the bulk semiconductor and sideways under the oxide layer (see insert of Fig. 5). Thus a junction curvature is formed near the corner of the diffusion mask. For a one-sided abrupt junction, this curvature causes a reduction of the breakdown voltage. In the present case with $N_B = 2.2 \times 10^{16}$ cm$^{-3}$, the breakdown voltage would be 36 V for a plane junction, and about 25 V for a junction with 1 $\mu$m curvature,[6] as shown by the circles in Fig. 5. Therefore the breakdown voltages for diodes $b$ and $c$ agree with theoretical expectation for a guard ring with 1 $\mu$m junction depth.

The above result confirms that a Schottky diode with a junction guard ring can have a breakdown voltage many times larger than one without a guard ring. In this example, breakdown occurred at the guard ring; but this result does not imply that the breakdown voltage of a Schottky diode is always limited by the curvature effect of the junction guard ring.

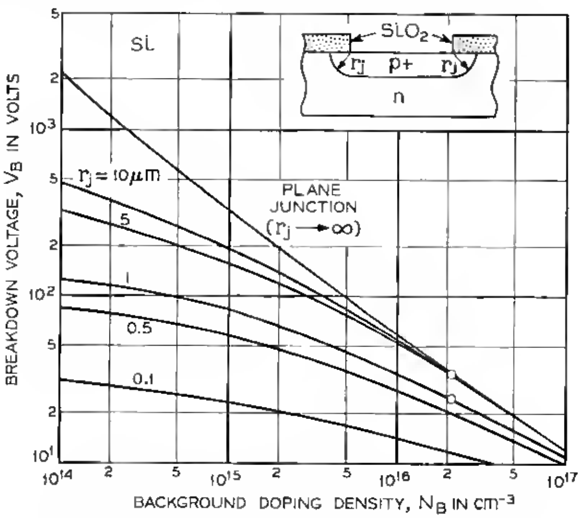


Fig. 5 — Theoretical results for silicon p⁺n junction with junction depth $r_j$ (insert) as the parameter. (See Ref. 6.)

By proper control of the diffusion process, one can form a linearly-graded junction with $V_B$ which is virtually independent of the junction curvature,[6] or one can form a composite junction (see insert of Fig. 6); that is, the space charge terminates in a graded region on one side of the junction and in a uniformly doped region on the other. The composite junction has a breakdown voltage always larger than an abrupt junction with the same junction curvature ($r_j$) and the same background doping ($N_B$). Some theoretical results of the composite junction are shown in Fig. 6.

In order to make a guard ring which has higher breakdown voltage than that of the Schottky diode, the following experiment was performed. An epitaxial silicon wafer with doping about $2 \times 10^{16}$ cm$^{-3}$ and a thickness of 8 $\mu$m was used to form the three structures as shown in Fig. 1. The diffused guard ring has a doping profile which can be approximated by a composite junction with a junction depth of 3.5 $\mu$m and an impurity gradient of about $2.5 \times 10^{21}$ cm$^{-4}$. The theoretical breakdown voltage for the guard ring is about 50 V and the breakdown voltage for the Schottky barrier is about $42 \pm 2$ V (shown in Fig. 6). Thus the Schottky barrier diode is expected to break down first. Figure 7 shows the I–$V$ characteristics of the Schottky diode with guard ring (diode $c$) which has a forward characteristic similar to that shown

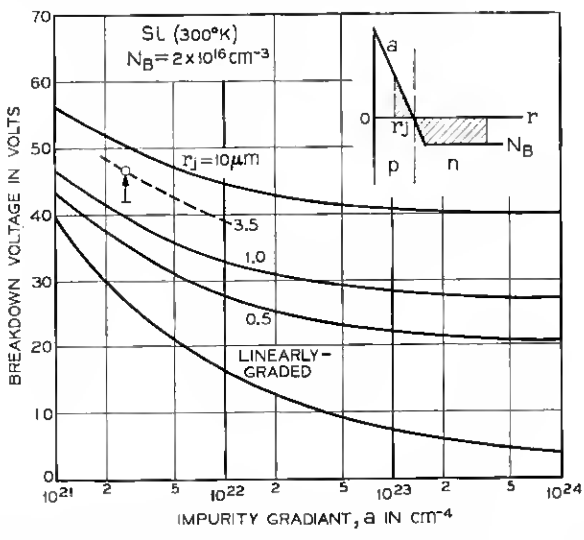


Fig. 6 — Theoretical results for silicon linearly-graded composite junction (insert) with junction depth as the parameter.

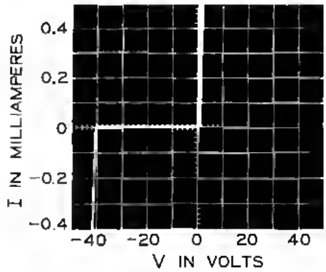


Fig. 7 — Oscilloscope current-voltage display of the characteristics of a Schottky diode with the ideal breakdown voltage ($N_D = 2.0 \times 10^{16}$ cm$^{-3}$).

in Fig. 3, and a reverse breakdown at about 41 V in good agreement with the expected result.

Figure 8 shows the forward and reverse $I$–$V$ curves for the three structures. For diode $a$ the forward and reverse characteristics are poor. For the p-n junction (guard ring alone, see Fig. 8b) the forward knee occurred at about 0.5 V and the reverse breakdown at 49 V. For diode $c$, the Schottky diode breaks down first at about 43 V. Because of the small junction area there is a large space-charge resistance, $R_{sc}$, under avalanche conditions. The value of $R_{sc}$ is given by[7] $R_{sc} \cong [W^2/A(2\epsilon V_d)]$ where $W$ is the width of depletion layer at breakdown, $A$ the junction area, $\epsilon$ the permittivity, and $V_d$ the limiting drift velocity. In the present case with $W \cong 3$ $\mu$m, $A = 2.5 \times 10^{-6}$ cm$^2$, and $V_d \cong 10^7$ cm per second, the value of $R_{sc}$ is 1.5 $K\Omega$, which is in good agreement with the slope shown in Fig. 7(c). (The junction temperature effect and the series resistance effect are calculated to be small compared with the above space-charge effect.) This further confirms that we have uniform breakdown of the Schottky diode. When the voltage reaches about 50 V, the p-n junction guard ring begins to break down similar to case $b$ (Fig. 8b). The space-charge resistance in this region is considerably lower because of the larger area of the guard ring.

### 2.4 *Surface Field Effect Study*

Notice in Fig. 1(c) that in addition to diffused $p^+$ guard ring, there is a metal-oxide-semiconductor structure surrounding the device. It is known that when a reverse bias is applied to the metal electrode, the surface space-charge region under the oxide is in nonequilibrium condition.[8]

It has been shown that a surface field has a profound effect on the breakdown of planar p-n junctions.[9] In order to study this effect on

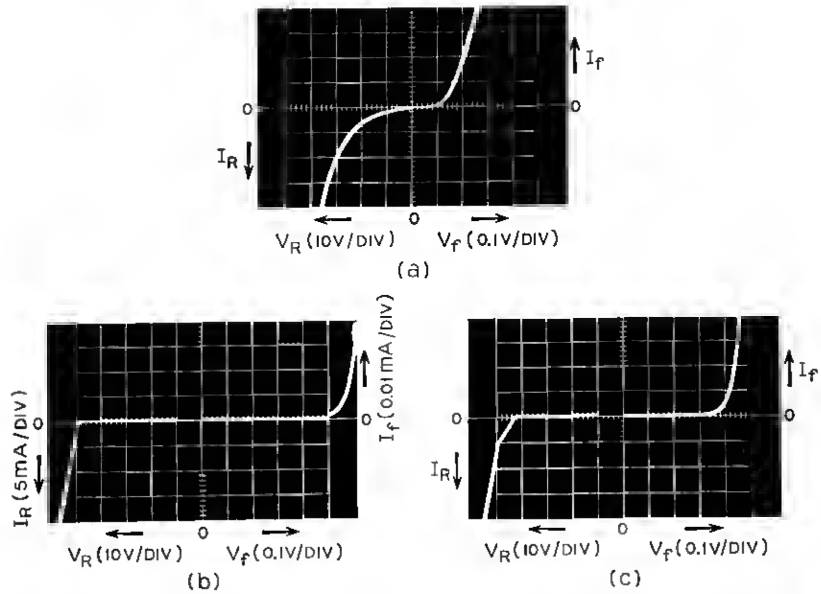


Fig. 8 — Oscilloscope display of the current-voltage characteristics for the structures shown in Fig. 1.

the breakdown voltage of Schottky barrier diodes, a separate metal electrode on the oxide (that is, the gate electrode) is fabricated as shown in Fig. 9. The fabrication procedures were the same as described previously. The samples used were ⟨111⟩ oriented, 1.0 ohm-cm, $n$-type silicon wafers. When a negative gate bias is applied, the surface field tends to smooth out the field concentration near the junction edge (see Fig. 10). Thus the radius of curvature, $r_j$, is effectively in-

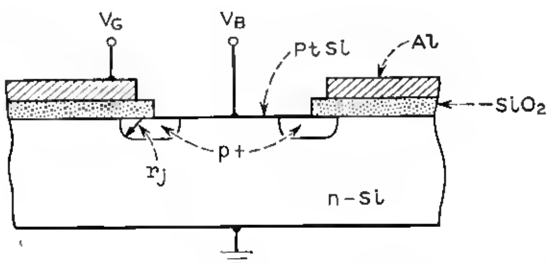


Fig. 9 — Schottky barrier diode with separate electrodes on PtSi and on the oxide.

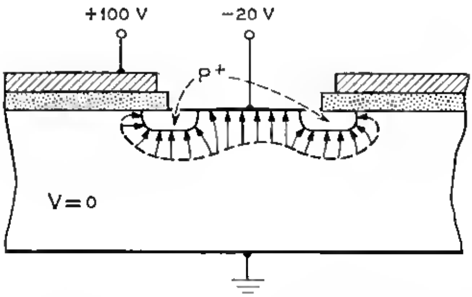


Fig. 10 — Electric field distribution for negative gate voltage.

creased. This in turn increases the breakdown voltage (the relationship between $V_B$ and $r_j$ has been shown in Fig. 5).

Figure 11 shows the field profile near the junction as a positive gate bias is applied, where the radius of curvature, $r_j$, is effectively reduced resulting in a decreased breakdown voltage. Figure 12 shows the measured reverse $I$–$V$ characteristics as a function of the gate voltage for a Schottky diode with a guard ring of 0.4 $\mu$m junctions depth. As expected, the gate voltage does have a profound effect on the junction breakdown voltage. Figure 13 shows the measured breakdown voltage versus gate voltage for four different junction depths. Notice that the breakdown voltages all approach the theoretical value ($\approx$100 V) as $-V_G$ increases. Also at zero bias, the breakdown voltage decreases as the junction depth $r_j$ decreases.

Similar effects are observed on a Schottky diode that has no p-n junction guard ring but has a second metal oxide semiconductor overlay as shown on the Fig. 14 insert, where $ZrO_2$ is formed near the periphery of the metal, and separate voltages are applied to the

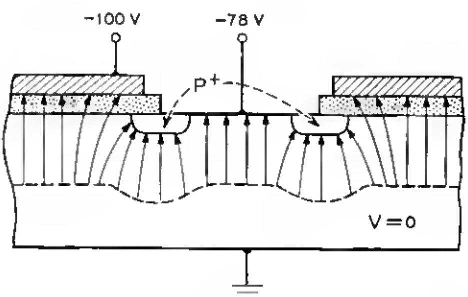


Fig. 11 — Electric field distribution for positive gate voltage.

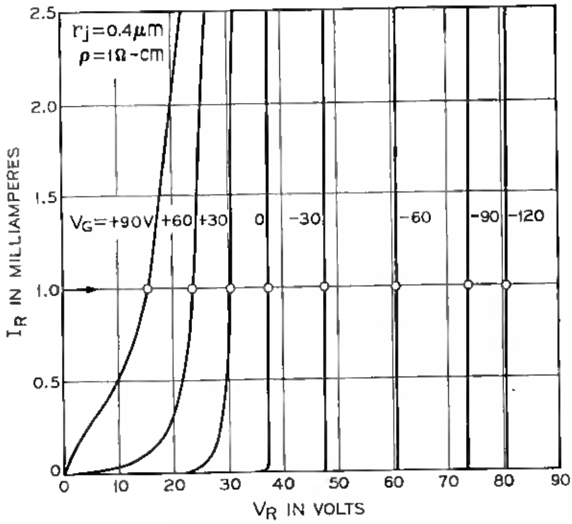


Fig. 12 — Reverse current-voltage characteristics as a function of the gate voltage on a Schottky diode with a p-n junction guard ring.

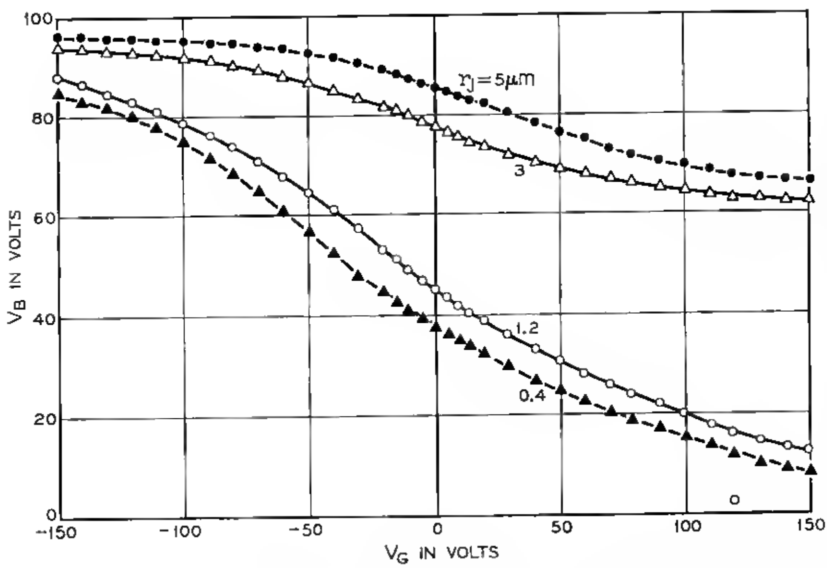


Fig. 13 — Measured breakdown voltage (at 1 ma) versus gate voltage for Schottky diode with p-n junction guard ring. The junction depths are 0.4, 1.2, 3, and 5 $\mu$m.

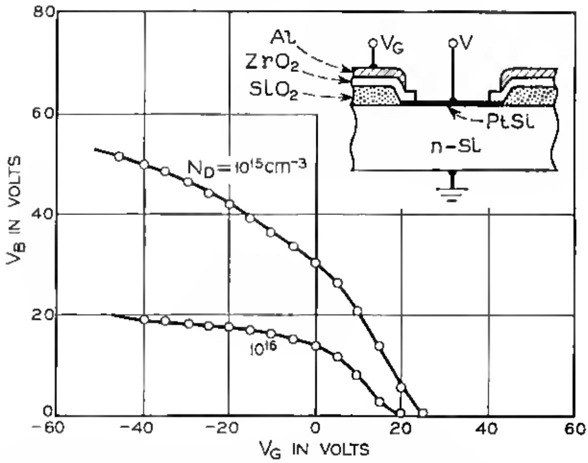


Fig. 14 — Measured breakdown voltage versus gate voltage for Schottky diode with a metal oxide semiconductor overlay near the periphery (insert).

diode and the metal oxide semiconductor guard ring electrodes. As the gate voltage increases in the negative direction, the edge field is gradually reduced, resulting in an increased breakdown voltage (here defined as voltage drawing 1 ma current). When $V_G$ increases in the positive direction, however, the enhanced edge field causes drastic lowering of the junction breakdown voltage as Fig. 14 shows.

## III. SUMMARY

It has been demonstrated that the breakdown voltage of a Schottky barrier diode can be made to approach the theoretical value of one-sided abrupt p-n junction with the same background doping. The much lower breakdown voltages usually obtained result from "edge effect" which can be modified or eliminated by proper use of either a diffused guard ring or a surrounding electrode. It has also been shown that the surface field can have profound influence on the guard ring breakdown characteristics. Since any planar diffused guard ring has a finite junction curvature ($r_j$), to eliminate the junction curvature effect one has to control the diffusion depth and diffusion profile such that the breakdown voltage of the guard ring is larger than that of the Schottky junction.

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